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and Properties

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Michael Bass Editor in Chief

*The Center for Research and
Education in Optics and Lasers (CREOL)
University of Central Florida
Orlando, Florida*

Eric W. Van Stryland Associate Editor

*The Center for Research and
Education in Optics and Lasers (CREOL)
University of Central Florida
Orlando, Florida*

David R. Williams Associate Editor

*Center for Visual Science
University of Rochester
Rochester, New York*

William L. Wolfe Associate Editor

*Optical Sciences Center
University of Arizona
Tucson, Arizona*

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- ρ mass density (kg/m^3)
 σ conductivity (S/m)
 ω radian frequency (s^{-1})

35.2 INTRODUCTION

Metals are commonly used in optical systems in three forms: (1) structures, (2) mirrors, and (3) optical thin films. In this article, properties are given for metal mirror substrate and structural materials used in modern optical systems. Many other materials have not been included due to their limited applicability. Metal film properties are discussed in the context of thick films (claddings) rather than optical thin films that are covered in Chap. 42, Optical and Physical Properties of Films and Coatings, in Vol. I. Since mirrors are structural elements, the structural properties are equally important as the optical properties to the designer of an optical system. Therefore, the properties addressed here include physical, mechanical, and thermal properties in addition to optical properties. Mechanical and thermal properties of silicon (Si) and silicon carbide (SiC) are included, but not their optical properties since they are given in the article entitled "Optical Properties of Semiconductors," Vol II, Chap. 36.

After brief discussions of optical properties, mirror design, and dimensional stability, curves and tables of properties are presented, as a function of temperature and wavelength, where available. For more complete discussions or listings, the reader should consult the references and/or one of the available databases.¹⁻³ A concise theoretical overview of the physical properties of materials is given by Lines.⁴

Nomenclature

The symbols and units used in this subsection are consistent with usage in other sections of this Handbook although there are some unavoidable duplications in the usage of symbols between categories of optical, physical, thermal, and mechanical properties. Definitions of symbols with the appropriate units are contained in the table at the beginning of this article.

Optical Properties

The definitions for optical properties given in this section are primarily in the geometric optics realm and do not go into the depth considered in many texts dealing with optical properties of solids.⁵⁻⁸

There is obviously a thickness continuum between thin films and bulk, but for this presentation, bulk is considered to be any thickness of material that has bulk properties. Typically, thin films have lower density, thermal conductivity, and refractive index than bulk; however, current deposition techniques are narrowing the differences. Optical properties of thin films are presented only when bulk properties have not been found in the literature.

The interaction between light and metals takes place between the optical electric field and the conduction band electrons of the metal.⁹ Some of the light energy can be

transferred to the lattice by collisions in the form of heat. The optical properties of metals are normally characterized by the two optical constants: index of refraction n and extinction coefficient k that make up the complex refractive index N where:

$$N = n + ik \quad (1)$$

The refractive index is defined as the ratio of phase velocity of light in vacuum to the phase velocity of light in the medium. The extinction coefficient is related to the exponential decay of the wave as it passes through the medium. Note, however, that these "constants" vary with wavelength and temperature. The expression for an electromagnetic wave in an absorbing medium contains both of these parameters:

$$E = E_0 e^{-2\pi kx/\lambda_0} e^{-i(2\pi nx/\lambda_0 - \omega t)} \quad (2)$$

where E_0 is the amplitude of the wave measured at the point $x = 0$ in the medium, E is the instantaneous value of the electric vector measured at a distance x from the first point and at some time t , ω is the angular frequency of the source, and λ_0 is the wavelength in vacuum.

The absorption coefficient α is related to the extinction coefficient by:

$$\alpha = 4k/\lambda_0 \quad (3)$$

and for the general case, the absorption coefficient also appears in the absorption equation:

$$I = I_0 e^{-\alpha x} \quad (4)$$

However, this equation implies that the intensities I and I_0 are measured within the absorbing medium. The complex dielectric constant ϵ for such a material is:

$$\epsilon = \epsilon_1 + i\epsilon_2 \quad (5)$$

where the dielectric constants are related to the optical constants by:

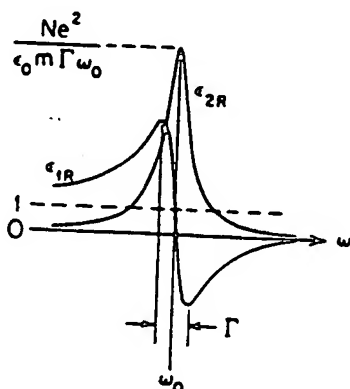
$$\epsilon_1 = n^2 - k^2 \quad (6)$$

$$\epsilon_2 = 2nk \quad (7)$$

Two additional materials properties that influence the light-material interaction are magnetic susceptibility μ and conductivity σ that are further discussed later.

The equations describing the reflection phenomena, including polarization effects in metals, will not be presented here but are explained in detail elsewhere.^{5-8,10-11} After a brief description of Lorentz and Drude theories and their implications for metals, particularly for absorption, the relationship among reflection, transmission, and absorption is discussed.⁹

The classical theory of absorption in dielectrics is due to H. A. Lorentz¹² and in metals to P. K. L. Drude.¹³ Both models treat the optically active electrons in a material as classical oscillators. In the Lorentz model, the electron is considered to be bound to the nucleus by a harmonic restoring force. In this manner, Lorentz's picture is that of


 FIGURE 1 Frequency dependences of ϵ_{1R} and ϵ_{2R} .

nonconductive dielectric. Drude considered the electrons to be free, and set the restoring force in the Lorentz model equal to zero. Both models include a damping term in the electron's equation of motion that in more modern terms is recognized as a result of electron-phonon collisions.

These models solve for the electron's motion in the presence of the electromagnetic field as a driving force. From this, it is possible to write an expression for the polarization induced in the medium and from that to derive the dielectric constant. The Lorentz model for dielectrics gives the relative real and imaginary parts of the dielectric constant ϵ_{1R} and ϵ_{2R} in terms of N , the number of dipoles per unit volume; e and m , the electron charge and mass; Γ , the damping constant; ω and ω_0 , the radian frequencies of the field and the harmonically bound electron; and ϵ_0 , the permittivity of free space. These functions are shown in Fig. 1. The range of frequencies where ϵ_1 increases with frequency is referred to as the *range of normal dispersion*, and the region near $\omega = \omega_0$ where it decreases with frequency is called the *range of anomalous dispersion*.

Since the ionic polarizability is much smaller than the electronic polarizability at optical frequencies, only the electronic terms are considered when evaluating optical absorption using the Lorentz model for dielectrics. The Drude model for metals assumes that the electrons are free to move. This means that it is identical to the Lorentz model except that ω_0 is set equal to zero. The real and imaginary parts of the dielectric constant are then given by

$$\epsilon_{1R} = 1 - (Ne^2\epsilon_0 m) \frac{1}{\omega^2 + \Gamma^2} \quad (8)$$

$$\epsilon_{2R} = (Ne^2\epsilon_0 m) \frac{\Gamma}{\omega(\omega^2 + \Gamma^2)} \quad (9)$$

The quantity Γ is related to the mean time between electron collisions with lattice vibrations, and by considering electronic motion in an electric field \mathbf{E} having radian frequency ω , an expression for the average velocity can be obtained. An expression for the conductivity σ is then obtained and the parts of the dielectric constant can be restated. At electromagnetic field frequencies that are low, it can be shown that $\epsilon_2 \gg \epsilon_1$ and therefore it follows that:

$$\alpha = (\omega\mu\sigma/2)^{1/2} \quad (10)$$

In other words, the optical properties and the conductivity of a perfect metal are related

through the fact that each is determined by the motion of free electrons. At high frequencies, transitions involving bound or valence band electrons are possible and there will be a noticeable deviation from this simple result of the Drude model. However, the experimental data reported for most metals are in good agreement with the Drude prediction at wavelengths as short as $1\text{ }\mu\text{m}$.

From Eq. (10) it is clear that a field propagating in a metal will be attenuated by a factor of $1/e$ when it has traveled a distance:

$$\delta = (2/\omega\mu\sigma)^{1/2} \quad (11)$$

This quantity is called the *skin depth*, and at optical frequencies for most metals it is $\sim 50\text{ nm}$. After a light beam has propagated one skin depth into a metal, its intensity is reduced to 0.135 of its value at the surface.

Another aspect of the absorption of light energy by metals that should be noted is the fact that it increases with temperature. This is important because during laser irradiation the temperature of a metal will increase and so will the absorption. The coupling of energy into the metal is therefore dependent on the temperature dependence of the absorption. For most metals, all the light that gets into the metal is absorbed. If the Fresnel expression for the electric field reflectance is applied to the real and imaginary parts of the complex index for a metal-air interface, the field reflectivity can be obtained. When multiplied by its complex conjugate, the expression for the intensity reflection coefficient is obtained:

$$R_i = 1 - 2\mu\epsilon_0\omega/\sigma \quad (12)$$

Since the conductivity σ decreases with increasing temperature, R_i decreases with increasing temperature, and at higher temperatures more of the incident energy is absorbed.

Since reflection methods are used in determining the optical constants, they are strongly dependent on the characteristics of the metallic surface. These characteristics vary considerably with chemical and mechanical treatment, and these treatments have not always been accurately defined. Not all measurements have been made on freshly polished surfaces but in many cases on freshly deposited thin films. The best available data are presented in the tables and figures, and the reader is advised to consult the appropriate references for specifics.

In this article, an ending of *-ance* denotes a property of a specific sample (i.e., including effects of surface finish), while the ending *-ivity* refers to an intrinsic material property. For most of the discussion, the endings are interchangeable.

Reflectance r is the ratio of radiant flux reflected from a surface to the total incident radiant flux. Since r is a function of the optical constants, it varies with wavelength and temperature. The relationship between reflectance and optical constants is:⁵

$$r = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \quad (13)$$

The reflectance of a good, freshly deposited mirror coating is almost always higher than that of a polished or electroplated surface of the same material. The reflectance is normally less than unity—some transmission and absorption, no matter how small, are always present. The relationship between these three properties is:

$$r + t + a = 1 \quad (14)$$

Transmittance t is the ratio of radiant flux transmitted through a surface to the total incident radiant flux and absorptance a is the ratio of the radiant flux lost by absorption to the total incident radiant flux. Since t and a are functions of the optical constants, the

vary with wavelength and temperature. Transmittance is normally very small for metals except in special cases (e.g., beryllium at x-ray wavelengths). Absorptance is affected by surface condition as well as the intrinsic contribution of the material.

The thermal radiative properties are descriptive of a radiant energy-matter interaction that can be described by other properties such as the optical constants and/or complex dielectric constant, each of which is especially convenient for studying various aspects of the interaction. However, the thermal radiative properties are particularly useful since metallic materials are strongly influenced by surface effects, particularly oxide films, and therefore in many cases they are not readily calculated by simple means from the other properties.

For opaque materials, the transmission is near zero, so Eq. (14) becomes:

$$r + a = 1 \quad (15)$$

but since Kirchhoff's law states that absorptance equals emittance, ϵ , this becomes:

$$r + \epsilon = 1 \quad (16)$$

and the thermal radiative properties of an opaque body are fully described by either the reflectance or the emittance. Emittance is the ratio of radiated emitted power (in W/m^2) of a surface to the emissive power of a blackbody at the same temperature. Emittance can therefore be expressed as either *spectral* (emittance as a function of wavelength at constant temperature) or *total* (the integrated emittance over all wavelengths as a function of temperature).

Physical Properties

The physical properties of interest for metals in optical applications include density, electrical conductivity, and electrical resistivity (the reciprocal of conductivity), as well as crystal structure. Chemical composition of alloys is also included with physical properties.

For density, mass density is reported with units of kg/m^3 . Electrical conductivity is related to electrical resistivity, but for some materials, one or the other is normally reported. Both properties vary with temperature.

Crystal structure is extremely important for stability since anisotropy of the elastic, electric, and magnetic properties and thermal expansion depend on the type of structure.¹⁴ Single crystals of cubic metals have completely isotropic coefficient of thermal expansion (CTE), but are anisotropic in elastic properties—modulus and Poisson's ratio. Materials with hexagonal structures have anisotropic expansion and elastic properties. While polycrystalline metals with randomly oriented small grains do not exhibit these anisotropies they can easily have local areas that are inhomogeneous or can have overall oriented crystal structure induced by fabrication methods.

The combined influence of physical, thermal, and mechanical properties on optical system performance is described under "Properties Important in Mirror Design," later in this article.

Thermal Properties

Thermal properties of metals that are important in optical systems design include: coefficient of thermal expansion α , referred to in this section as CTE; thermal conductivity k ; and specific heat C_p . All of these properties vary with temperature; usually they tend to decrease with decreasing temperature. Although not strictly a thermal property, the maximum usable temperature is also included as a guide for the optical designer.

Thermal expansion is a generic term for change in length for a specific temperature

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